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Tracking of the broadbill swordfish, *Xiphias gladius*, in the central and eastern North Atlantic

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ABSTRACT

A total of 21 swordfish, *Xiphias gladius*, were tagged with pop-up satellite tags in northern and southeastern areas of the North Atlantic Ocean. There were seasonal patterns in the horizontal movements, with fish tagged in the central North Atlantic moving southwards from the end of the year, generally south of 25°N, and returning to the temperate foraging grounds, north of 40°N, in spring. Although movements mainly took place latitudinally, fish tracks showed connectivity between the north central, north western, south eastern and north eastern North Atlantic. Average estimated daily displacements were 24.7±19.5 km day^{-1}, and could average up to ~100 km day^{-1} in some months. The longest track recorded totaled more than 10,000 km. Swordfish showed remarkable physiological versatility, inhabiting waters with SSTs ranging from 10.1 to 28.6 °C, and subject to environmental temperatures of *c.* 4 °C–28° C, with daily ranges frequently over 15 °C (mean 9.2 ± 5.7). Fish showed a clear diel pattern in vertical behavior, feeding at 300–600 m deep during daytime and staying in the mixed layer at night. There was a significant relationship between nocturnal depth and moonphase, quarter and sea surface temperature. The results of the present study are in agreement with the current separation between North Atlantic, Mediterranean and South Atlantic stocks, but suggest that the assumption of a single homogeneous stock in the North Atlantic might be overly simplistic. Further tagging studies, with special emphasis in areas and seasons not covered so far and in combination with other techniques, are still needed to elucidate the uncertainties of Atlantic swordfish stock structure.

1. Introduction

The broadbill swordfish, *Xiphias gladius*, is the most widely distributed billfish species (Palko et al., 1981). It is also the most important in terms of commercial interest, and there are fisheries targeting this species with different gears all over the world (FAO, 2012).

The status of the swordfish stocks varies depending on the ocean and population considered. Latest stock assessments indicate swordfish stocks are overexploited in the Mediterranean Sea, moderately to over-exploited in the South Pacific stock/s considered (depending on the region and model assumptions), and underexploited in the Indian Ocean in the last year of the assessment model (2009), after a reduction of the fishing effort and catches (Anon, 2012; Hinton and Maunder, 2011; Davis et al., 2013; Anon, 2011).

In the Atlantic Ocean, swordfish are managed by the International Commission for the Conservation of Atlantic Tunas (ICCAT). Past assessments (before 1999 and 2002 for the southern and northern stocks, respectively) indicated the Atlantic stocks were overfished and that overfishing was occurring. However, the most recent assessments and fishery indicators suggest a successful recovery of both stocks, attributed to catch limits and other regulations implemented at national and multilateral level (Anon, 2012; Neilson et al., 2013; Anon, 2013; Anon, in press). The management actions and other factors (mainly catches lower than total allowable catch) have resulted in a recovery of the Atlantic populations to levels that would support the maximum sustainable yield (MSY). However, the results mentioned above are subject to uncertainties related to the biology of the species (e.g., growth and maturity schedules) and other factors, like the conflicting trends among standardized catch-per-unit effort indices. One of the main limitations in current stock assessments is the lack of a

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precise knowledge on the structure of the stocks and boundaries. In the Atlantic Ocean (including the Mediterranean Sea) swordfish is managed as three different stock units, namely North Atlantic and South Atlantic, separated at 5°N, and a Mediterranean stock. The ICCAT have defined the stock structure of the swordfish based on a pool of scientific evidence obtained over decades, such as detailed fishery data, biology parameters, tagging results, trends of abundance, size information and genetic studies (Anon, 2007). Recent genetic studies have shown a clear genetic differentiation between the Atlantic, Indian and Pacific Oceans versus the Mediterranean Sea. Little genetic differentiation within the North Atlantic was found in several studies and small but significant genetic differences were obtained between the North and South Atlantic units considered. However, the debate about the stock structure and boundaries between the Atlantic units and in other oceans remains unresolved. Moreover, recent pop-up tagging studies (Neilson et al., 2009, 2013) indicate relatively low mixing between the swordfish of the westernmost and the central-eastern areas of the North Atlantic, probably suggesting a more complex geographic stock structure than is currently assumed.

Conventional tagging is a useful and complementary tool for the definition of stock units and boundaries, and has provided information about swordfish growth (Restrepo, 1990; Kasapidis et al., 2007), and movements and mixing among Atlantic areas (for review, see Neilson et al., 2007), despite the low level of tag reporting, as compared with tunas, other billfish or large pelagic sharks (Anon, 2007). Post-release mortality, caused by the low resilience of swordfish to the fishing gears used, is a limitation for successful tagging experiments on this species (e.g., Abascal et al., 2010), in addition to the disappointing low number of conventional tags recoveries regularly reported – 3.6% on average according to the ICCAT Secretariat database current to March 2006 (Neilson et al., 2007). Information from conventional tags depends on the spatio-temporal tagging design, the fishing effort distribution of the fleets potentially recovering tagged fish, the reporting rate by fleet, as well as many other factors. Previous conventional tagging studies have indicated that conclusions about stock structure and mixing of swordfish in the North Atlantic based on conventional tagging studies are highly dependent on the spatial and temporal strata covered by the experiments (e.g., Tal Sperling et al., 2005). Wider tagging designs regularly produce a broader overview of the movements of large pelagic fish, as was the case for Atlantic swordfish when the tagging activities were geographically expanded (García-Cortés et al., 2003, Mejuto et al., 2005; Anon, 2007).

Electronic tags have proven to be a useful tool for the study of the movements and habitat preferences of large pelagic species in recent years (Nielsen et al., 2009). The main advantage of this technology is that it is, to a large extent, fishery independent, since fish can be tracked outside of the fishing grounds. However, limitations related to swordfish handling resilience have only allowed for the deployment of tags attached externally (e.g., Carey and Robinson, 1981; Sedberry and Loefer, 2001; Takahashi et al., 2003; Loefer et al., 2007; Neilson et al., 2009; Abascal et al., 2010; Sepulveda et al., 2010; Dewar et al., 2011; Hoolihan et al., 2011; Abecassis et al., 2012; Evans et al., 2014) in contrast with other methodologies (e.g., implantable archival tags) extensively used in other large pelagic species.

Investigations on large scale movements of swordfish based on electronic tagging techniques are very recent. Takahashi et al. (2003) described a cyclic migration pattern of swordfish off east Japan based on the temperature records of an externally attached archival tag. More recently, pop-up satellite tags (PSATs) have been used to describe the movement of swordfish in the south Pacific (Holdsworth et al., 2007; Abascal et al., 2010; Evans et al., 2014) and North Pacific Ocean (Dewar et al., 2011; Abecassis et al., 2012).

The only study carried out so far in the Atlantic Ocean (Neilson et al., 2009) found that fish tagged off eastern Canada carried out long distance migrations, and displayed a consistent pattern of movement, with residence in temperate waters from June to October, followed by a southwards migration to the Caribbean Sea, with fish remaining there until April and then returning to the same feeding grounds. The results of that study, with fish mainly moving latitudinally and never east of 55°W, question the current assumption of a single stock in the North Atlantic Ocean.

The objective of this study was to contribute to the knowledge on migrations and habitat preferences of swordfish in the North Atlantic Ocean, using pop-up satellite archival tags in the central and eastern North Atlantic, areas which have not been previously covered.

2. Materials and methods

A total of 21 swordfish were tagged using MK10 PSATs from Wildlife Computers. Fourteen PSATs were deployed in October–November 2008 southeast of the Grand Banks, around 35°N–45°N and 040°W–050°W. The remaining seven fish were tagged in December 2010 north of the Cape Verde archipelago, around 20°N–23°N and 020°W–025°W (Table 1).

Tagging was carried out opportunistically during the fishing activity of two commercial surface longliners targeting swordfish. Tags were attached by a monofilament leader with silicone tubing to a nylon dart. Tags were inserted into the dorsal musculature of the swordfish close to the first dorsal fin with the aid of a tagging pole once the fish was brought alongside the vessel. A conventional spaghetti tag was also placed around the monofilament for identification of the fish after the pop-up tag release in case of further recapture (Neilson et al., 2009). Only fish in seemingly prime conditions and measuring more than 135 cm lower jaw fork length (*ca.* 30 kg in round weight) were selected and tagged (mean 160±19 cm, range 135–215 cm). Both length and weight of the fish were visually estimated with the assistance of the crew.

Tags were programed to summarize data on time-at-temperature and time-at-depth in predefined bins at intervals of 6, 12 or 24 h (Table 1), and the deployment duration was set at 365 days. Depth bin limits were set at 0, 10, 25, 50, 75, 100, 150, 200, 250, 300, 350, 400 and 600 m, and temperature bin limits were 5, 10, 12, 14, 16, 17, 18, 19, 20, 22, 24, 26 and 28 °C. Tag transmitted information was first processed using manufacturer software (DAP processor, Wildlife Computers). Tracks were estimated by Collecte Localisation Satellite (CLS, Ramonville Saint-Agne, France) using a Kalman filter/smoother approach constrained by light-level, sea surface temperature (daily fields obtained at a 9 km resolution by blending microwave and infrared SST from REMSS) and bottom topography (ETOPO2) as described in Royer and Lutcavage (2009).

Information on vertical behavior was analyzed in relation to the area and time of the day. Due to the diel pattern in vertical behavior, only those histograms that were estimated to take place completely during daytime or nighttime were selected. Sunrise and sunset times were calculated using the Matlab script "sunrise", from the Woods Hole Coastal and Marine Science Center. A generalized linear model, followed by ANOVA, was used to analyze the relationship between nighttime median depth (calculated using the center of the depth bins) and sea surface temperature (as measured by the tag), quarter of the year and moon visible fraction (from the United States Naval Observatory, available at http://aa.usno.navy.mil/data/docs/MoonFraction.php).

Maps were constructed using Matlab R2011b m_map package (Pawlowicz, 2011), and plots were performed in R (R Core Team, 2013), using packages ggplot and plotrix. Data analysis was